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14. ABSTRACT

This report results from a contract tasking University of Bath as follows: We propose to develop a new approach to the guiding and focusing of THz radiation aimed at applications in civil defence imaging and monitoring. Our approach uses what we call a 'metawire', a cylindrical wire decorated with a regular array of grooves. Borrowing on concepts from the engineering of planar metamaterials, such a wire can guide THz radiation with strong confinement in the form of electromagnetic surface modes. In addition, focusing to volumes far below the diffraction limit into the micron and possibly sub-micron level is possible in tapered structures. We have so far conducted proof-of-principle electromagnetic simulations showing the feasibility of this concept, and now want to move to the real-world development of this technology, leading to compact devices for THz probing in confined spaces. Additionally, we want to make a push into active THz near-field probing by designing near-field probes with integrated receivers pumped by hollow-core photonic crystal fibres, to enable flexibility in THz device characterization.

Applications of a THz metawire in the civil defence sector are likely to include:
a) highly integrated THz guiding and routing structures allowing easy interfacing to sources / detectors
b) sensitive THz sensors for explosives, civil defence agents, etc.
c) the development of a new THz imaging technology offering possibly sub-micron scale resolution

15. SUBJECT TERMS
EOARD, metamaterials, terahertz technology

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THz Metawires: Near-field probing and super-focusing in the far-IR

FA8655-07-1-3045

Final Performance Report
Oct 2008

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and

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Objectives:

Task	*Progress*	*Completed*
Verification of initial theoretical designs of metawires & focusing structures		☑
Exploration of different fabrication routes of metawires based on laser machining and mechanical milling	☑	
Investigation of new geometries such as helical grooves		☑
Experimental study and optimization of broadband coupling to unstructured wires and metawires, including the development of efficient radially polarized sources		☑
Experimental demonstration of spoof SPP propagation along metawires		☑
Work towards pilot studies of spectroscopy and sensing using metawires	☑	

Status of effort at end of performance period:

Based on our initial theoretical description of electromagnetic surface wave propagation along structured wires (*metawires*) at THz frequencies [1], we have extended our numerical modelling capabilities to more complex wire geometries and focusing structures. Specifically, we have obtained evidence that also wires with a helical, screw-like thread support highly confined electromagnetic surface wave propagation, which we have experimentally verified. In parallel with these efforts, we have extended our experimental setup for the excitation and probing of these so-called spoof surface plasmon polaritons (SPPs), and developed efficient radially polarized receivers. In a pilot experiment using a helical wire we were indeed able to map out the dispersion characteristics of the three lowest-order spoof SPP modes.

Based on these results, we are currently (with support from AFOSR funds from Dr. Gernot Pomrenke) refining our experimental capabilities to near-field probing for field-mapping, and are working on setups for chemical detection using THz time domain spectroscopy with spoof SPP modes.

Accomplishments:

Please note that for convenience this report includes relevant background theory and results first reported in the interim report on FA8655-07-1-3045.

Theoretical investigations of THz spoof SPP propagation on metawires

Spoof surface plasmon polaritons (SPPs) are electromagnetic surface waves propagating at the interface of a structured very good (perfect) conductor with a dielectric, and have first been described theoretically in a seminal paper by Pendry [2]. These waves resemble SPPs at visible frequencies in terms of the ability to confine electromagnetic energy tightly to the interface, but with one important difference. While at visible frequencies the localization is due to the coupling of the electromagnetic fields to the electron plasma of the metal, spoof SPPs are localized due to purely geometrical effects – the fields interact with the sub-wavelength surface topology with acts as a periodic arrangement of small, coupled cavities. This way, concepts from plasmonics can be extended into the far-infrared and microwave regime.

While all theoretical descriptions of this phenomenon so far have focused on planar surfaces structured with regular arrays of grooves or holes, we have applied this approach to cylindrical geometries. Our goal is the creation of an efficient “stick” for the high-confinement guiding of THz radiation.

A 3D rendering of the device is shown in Fig. 1; it consists of a metallic wire of radius R, regularly corrugated with annular rings of depth $h=R-r$. As with our planar designs for THz waveguides investigated in our existing AFOSR program, spacing of the corrugations with a periodicity significantly below the wavelength of interest results in the creation of a metamaterial with designed electromagnetic properties. In our case, the *metawire* is designed so to sustain highly confined THz surface waves.

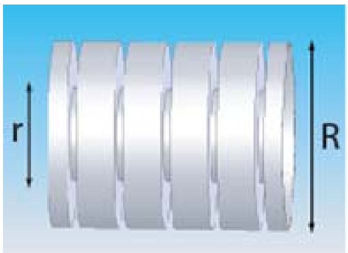

Figure 1. Three-dimensional rendering of a metawire.

Examples of typical dispersion curves for the lowest-order surface mode are shown in Figure 2a. As can be seen, the curves lie to the right of the light line, and resemble those of surface plasmon polaritons (SPPs) at visible frequencies. However, in our case the modes are established solely due to the geometrical surface structure, and are supported even in the limit of perfect conductors – hence the name “spoof” surface plasmon polaritons adopted in the initial description of such modes on perforated flat films [2]. It is also apparent that the asymptotic frequency at the edge of the Brillouin zone - the analogue to the surface plasmon frequency in the visible - decreases with increasing groove depth, leading to stronger confinement. This is exemplified in the field plots in Figure 3. Apart from this lowest order mode, also higher, whispering-

gallery-type modes are supported inside the grooves (Figure 2b), which are however not of immediate interest for practical applications of such a metawire.

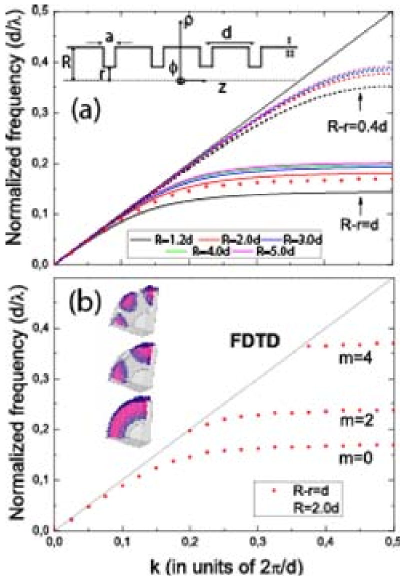

Figure 2. a) Normalized dispersion relation of spoof SPP modes sustained by a corrugated wire calculated using an analytical model (solid lines) and FDTD (dots). b) Dispersion and field plots of the fundamental (m=0) and some higher order modes.

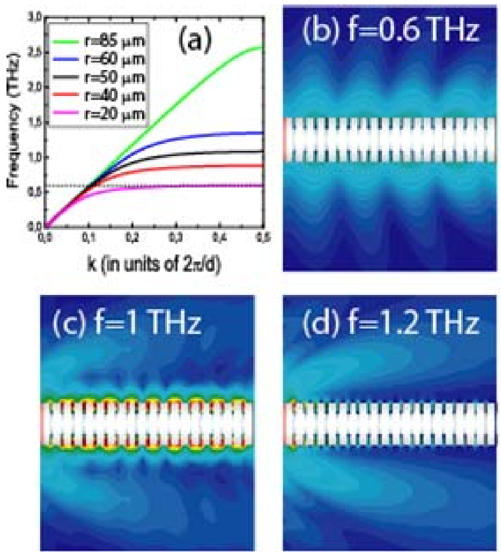

Figure 3. a) Dispersion relation for spoof SPPs on 100 μm thick metal wires. Deeper grooves (smaller inner radius r) lead to a stronger mode confinement (more significant bending of the dispersion curve to the right of the light line). b-d) Field-plots of spoof SPPs on an R=100 μm, r=20 μm wire optimized for guiding at 1 THz (c). Below this frequency, the waves are less confined (b), while no guiding takes place at higher frequencies (d). Compare with pink dispersion curve in (a).

We have extended these initial descriptions of metawires published by us in [1] via more detailed investigations of the energy confinement, with a focus on tapered structures allowing super-focusing of THz radiation. What we have in mind is a wire with fixed groove depth, but gradually reducing outside diameter. Figure 4 shows how the dispersion of the supported spoof SPPs bends away further and further from the light line with a reduction in outer diameter, leading to a tighter confinement of the surface waves as they approach the apex of the taper.

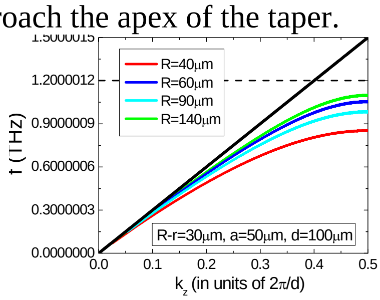

Figure 4. Dispersion relation of spoof SPPs propagating along metawires of fixed groove depth, width and period, but reducing outer diameter. Fields plots at the frequencies indicated are shown in Figure 5.

Examples of field plots are shown in Figure 5, clearly demonstrating the ability of this concept for the efficient focusing of THz radiation.

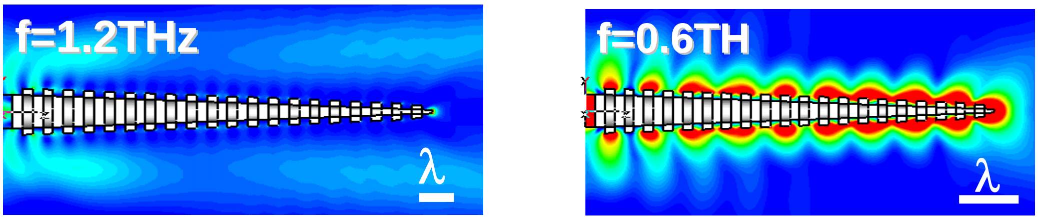

Figure 5. Electric field distributions along a tapered metawire with the dispersion of Figure 4. At frequencies above the band edge (right), no guiding takes place, while for lower frequencies reduction in diameter results in efficient focusing (left).

Helical metawires supporting spoof SPPs

In addition to our studies of metawires with regular arrays of grooves, we have also investigated wires corrugated with helical, screw-like grooves. Such wires are available commercially, and exhibit interesting polarization properties. In order to verify the existence of electromagnetic surface waves in this geometry, we have modified a home-written finite-difference time-domain code in order to allow the direct computation of the supported modes in a unit cell of a helical metawire. The geometry and dispersion relation of supported modes are shown in Figures 6 and 7 for a helical wire with an outer diameter of 2 mm, periodicity 0.4 mm, groove width 0.23 mm and groove depth 0.2 mm. As apparent from the dispersion relation, a multitude of surface modes (bands below the light line) are supported.

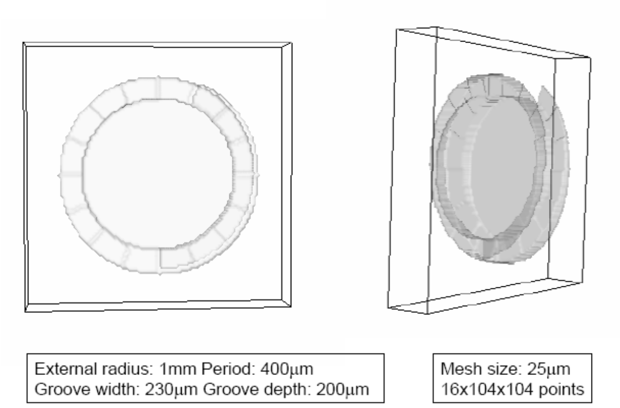

Figure 6. Geometry of the unit cell of a helical metawire.

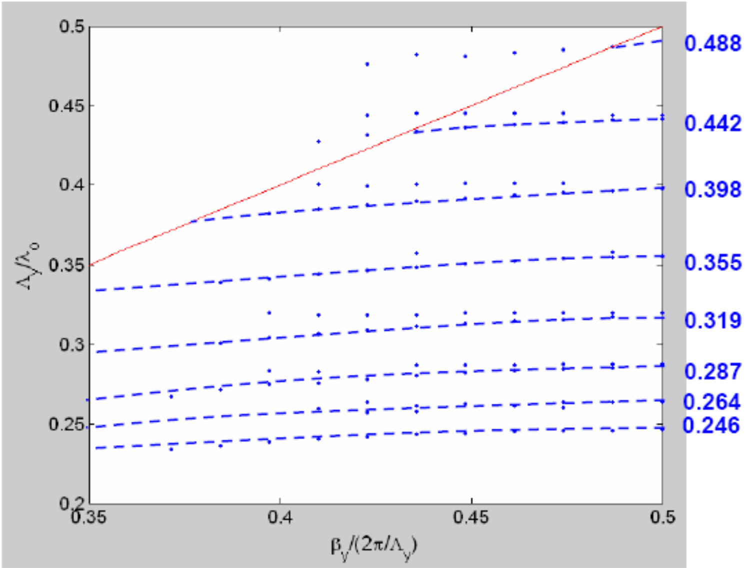

Figure 7. Dispersion relation (normalized frequency vs. normalized wavevector) near the zone boundary. Compare to Figure 2b for normal metawires.

Figure 8 shows examples of the electric field distribution for the lowest-order and a number of higher-order modes at the zone boundary, resembling as expected whispering-gallery modes inside the unit cell due to the requirement of translational symmetry.

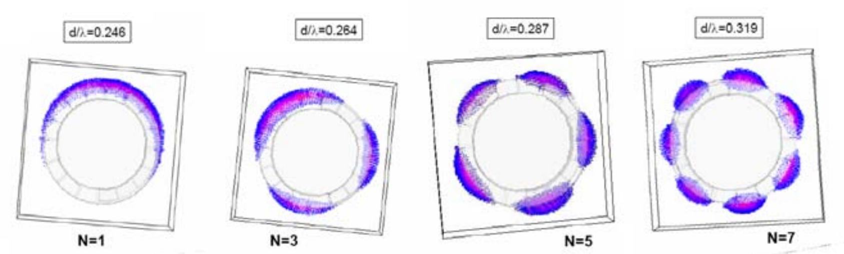

Figure 8. Mode profiles at the zone boundary of the lowest and a couple of higher order modes with the dispersion of Figure 7.

<u>Experimental efforts</u>

Our experimental setup for the investigation of spoof SPP propagation along metawires is an extension of our existing time-domain setup used for our program on planar structured materials supporting spoof SPPs, built via direct support from AFOSR (Gernot Pomrenke). Figure 9 shows a picture of a helical metawire mounted in the centre of the setup. We have investigated coupling to metawires and helical wires using both aperture and end-fire coupling. End-fire coupling has proven to be the method of choice, and bending of the wire ensures that no free-space radiation reaches the detector. *The fact that our metawires can be bent without significant radiation loss of the guided surface waves clearly demonstrates their potential as THz waveguides and probes.*

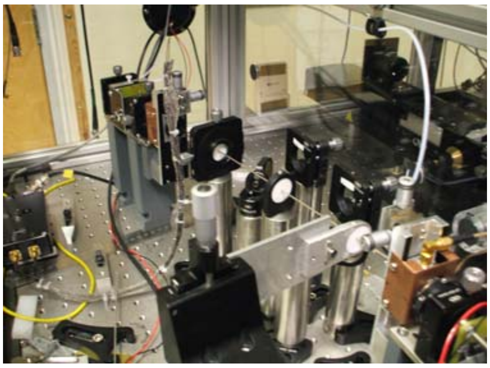

Figure 9. Experimental setup for probing THz spoof SPP propagation along metawires. The supported wire is visible in the centre of the picture.

Experimental results are reported in Figure 10, showing a time domain trace and the corresponding frequency spectrum of a radially polarized pulse guided along a helical metawire of outer radius 1.2 mm and pitch 0.4 mm, and comparing it to that of a flat wire. The ringing in the time domain trace is due to the delayed surface waves, with the Fourier spectrum showing pronounced peaks corresponding to the cut-off frequencies of the three lowest order SPP modes supported by the structure.

This constitutes the first experimental demonstration of spoof SPP-like propagation of electromagnetic energy on metawires, the central goal of our performance period.

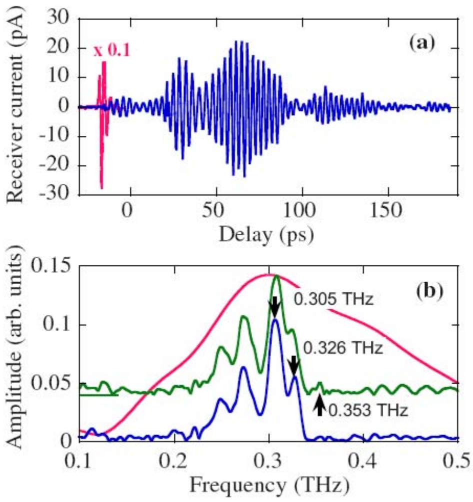

Figure 10. Time trace (top) and spectrum (bottom) of spoof SPPs (blue and green curves) propagated along a helical metawire of outer diameter 1.2 mm with 400 μm pitch, compared to data obtained on a smooth wire (pink curve). Peaks corresponding to the cut-off frequencies of the first three lowest order spoof SPP modes are clearly discernable.

In support of our experimental observations and the associated interpretation, Figure 11 shows numerical results obtained both for the dispersion and the propagation of the three-lowest order modes supported by the metawire. The cut-off frequencies are in excellent agreement with the peaks in the experimentally observed frequency spectrum.

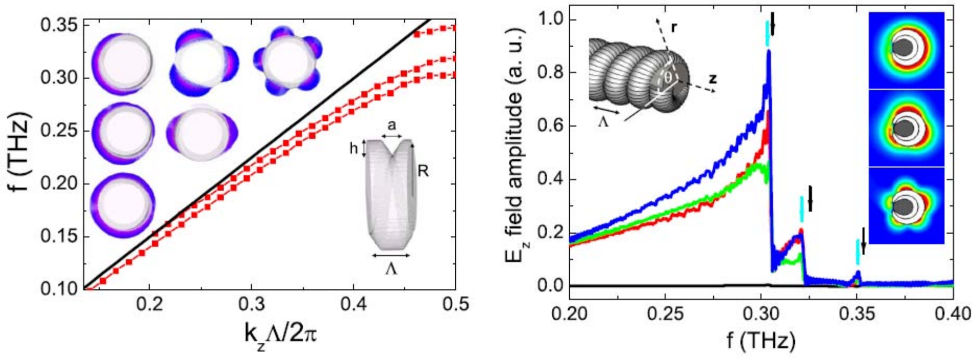

Figure 11. Numerical results for both the dispersion (left) and the propagation (right) of the three lowest-order spoof SPP-like modes supported by our structure. The cut-off frequencies obtained using finite-difference time-domain simulations are in excellent agreement with the experimentally observed peaks in the Fourier spectrum.

<u>Assessment of fabrication efforts:</u>

Our previous first result of a fabrication trial of a straight metawire based on laser machining is shown in Figure 12. As apparent, the necessary parameter space in terms of groove width, period and depth for THz spoof SPP propagation is accessible. We have implemented this groove shape into our modelling, which suggests only negligible effects for a change from rectangular to triangular grooves of same depth.

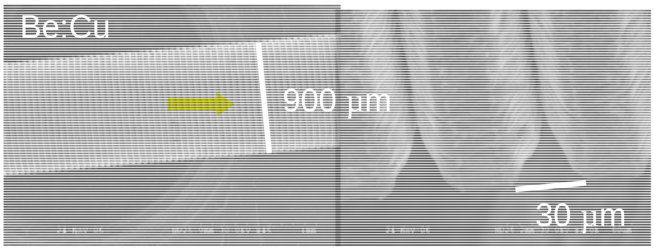

Figure 12. First example of a metawire fabricated using laser machining. Note the triangular shape of the grooves.

In Figure 13 we present the first example of a micromachined metawire with a pitch of 0.4 mm. The experimental data obtained for spoof SPP propagation on these fabricated wires is however currently not of the same quality as those published using the commercially sourced helical structure. We attribute this to poor control over the groove shape using both laser machining and mechanical milling using our initial facilities.

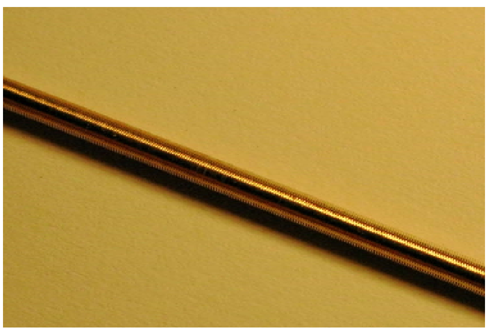

Figure 13. First example of a metawire fabricated using micromachining (pitch 0.4 mm).

Development of optimized sources and receivers for THz metawire excitation:

In order to ensure a reasonable mode matching for end-fire coupling to metawires, we have developed and optimized radially polarized transmitters and receivers. A comparison of the frequency spectra of representative developed sources to one of our standard linear polarized transmitters is shown in Figure 14. A significant improvement in launching efficiency of spoof SPPs was obtained via the development of a screened Ge-based device with a silica and germanium coating and a small aperture for low-divergence end-fire coupling. We are currently investigating further improvements of this scheme, in order to be able to quantify a coupling efficiency.

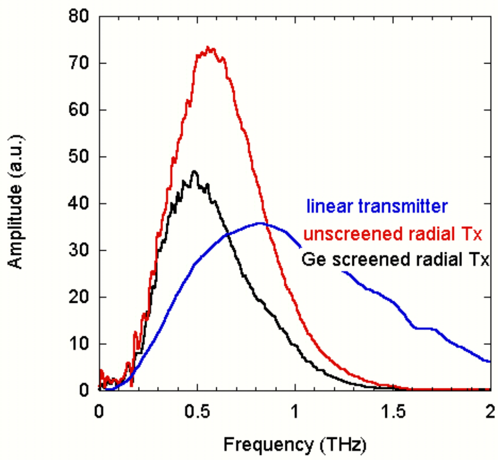

Figure 14. Comparison of bandwidth of standard linear and newly developed radially polarized THz transmitters.

References:

1. Maier, S.A., et al., *Terahertz surface plasmon polariton propagation and focusing on periodically corrugated metal wires.* Physical Review Letters, 2006. **97**: p. 176805.
2. Pendry, J.B., L. Martin-Moreno, and F.J. Garcia-Vidal, *Mimicking surrface plasmons with structured surfaces.* Science, 2004. **305**(5685): p. 847.

Further steps:

Our current and future research into THz metawires, supported using additional funds from Dr. Gernot Pomrenke, will focus on the following thrust areas.

- Development of near-field probes for a direct mapping of the spoof SPP field, based on the approach by Mitrofanov and colleagues (APL 77, 591). Fabrication trials based on reactive ion etching on arsenic implanted GaAs wafers are currently underway.
- Explore geometries amendable for surface-enhanced chemical and biochemical sensing.

Relevance:

The results obtained in our performance period constitute the first observation of spoof surface plasmon polaritons at THz frequencies on structured wires (metawires). We have demonstrated that the surface pattern necessary for high confinement is of a form that can be fabricated using well-established microfabrication techniques such as laser machining or mechanical milling; however at this point commercially sourced helically grooved metawires show superior performance to microfabricated ones. Both numerical electromagnetics simulations and experiments using developed radially polarized sources have shown the possibility of exciting up to three lowest-order spoof SPP modes on metawires, and we have established a clear understanding of their dispersive and polarization properties.

Relevance to AF and civilian technology challenges:

The fact that sub-wavelength localization of THz waves can be achieved by surface patterning in a geometry that is within the realms of current microfabrication techniques is very encouraging. We expect such surfaces to enable:

a) a new class of highly integrated THz guiding and routing structures, with direct source and detector integration
b) sensitive THz sensors for explosives, civil defense agents, etc.
c) the development of a THz new imaging technology offering possibly micron scale resolution

Personnel Support:

Faculty: Prof. Stefan Maier (PI), Dr. Steve Andrews (co-PI)

PhD students: Chris Williams (department-funded, time spent on project: 100%)

Collaborators (visiting scheme funded by Royal Society UK):

Faculty: Prof. Francisco García-Vidal (Universidad Autónoma de Madrid, Spain),
Prof. Luis Martín-Moreno (Universidad de Zaragoza, Spain)

Publications:

Publications resulting from this funding period:

Fernández-Domínguez, Williams, García-Vidal, Martín-Moreno, Andrews, Maier, *APL* **93**, 141109 (2008)

Fernández-Domínguez, Maier, Andrews, Martin-Moreno, García-Vidal, “THz metawires”, *IEEE Selected Topics in Quantum Electronics* (accepted 2008)

Previous relevant publication under AFOSR funding (Dr. Gernot Pomrenke):

Maier, Andrews, Martin-Moreno, García-Vidal, “Terahertz surface plasmon polariton propagation and focusing on periodically corrugated metal wires”,
Physical Review Letters **97**, 176805 (2006)

Interactions and Transitions:

a) Conferences and Seminars (all invited)

SPIE Annual Meeting, San Diego, CA, 2008
Gordon Conference on Plasmonics, Tilton NH, 2008
Conference on Precision Electromagnetic Measurements, Broomfield CO, 2008
Photonics Europe, Strasbourg, France, 2008
OFC, San Diego, February 2008
Physics of Quantum Electronics, Snowbird, January 2008
International Congress on Metamaterials, Rome, October 2007
SPIE Annual Meeting, San Diego, August 2007
Surface Plasmon Photonics 3 (SPP3), Dijon, France, June 2007
European Materials Research Society E-MRS Spring Meeting, Strasbourg, June 2007
Progress in Electromagnetic Research PIERS, Beijing, March 2007

b) Consultations and Advisement

None.

c) Transitions

Upon advisement of Dr. Pomrenke, we have started talks with the Propulsion Directorate (AFRL/RZ) at Wright-Patterson AFB regarding the use of metawires for flame analysis.

Discoveries and patents:

None.

Honors and Awards:

None.